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DETERMINE THE ABSOLUTE ROUGHNESS OF PHENOLIC DUCT

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DETERMINE THE ABSOLUTE ROUGHNESS OF PHENOLIC DUCT

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ABSTRACT

An experimental program was conducted to measure the relative and absolute roughness of phenolic duct systems connected with a four-bolt flange and cleat joint. Ducts with seven distinct rectangular cross sections (internal aspect ratios $1 \leq W/H \leq 4$) were investigated. In every instance, the duct material thickness was 7/8 in. (22 mm), with smooth aluminum foil covering the internal surface between flanges. For *unreinforced* phenolic ducts with 10 ft (3.0 m) sections connected by four-bolt flanges, the relative roughness ε/D_h ranged from 0.0002 to 0.0005, with an average value of 0.0003. For similar ducts having 5 ft (1.5 m) duct sections (double the number of flanges per test section), the relative roughness range and average doubled. It appears that the flanges are the dominant effect on relative roughness and that the ducts tested have about 1.5 to 2.8 times more absolute roughness than the average value for galvanized steel ducts described in the ASHRAE Handbook. One additional case considered in this study indicated that the zero-length loss coefficient for an individual *internal cross reinforcement* $\acute{C}$ = 0.080, assuming that each reinforcement assembly contributed equally to the overall pressure loss in the test section. When compared at the same volume flow rate to unreinforced ducts, the presence of internal cross reinforcements more than doubled the measured pressure loss per unit length, for the specific geometry of reinforcement and duct cross section considered.

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NOMENCLATURE

A	=	Duct cross-section, m^2 (ft^2)
A_i	=	Nozzle area, m^2 (ft^2)
C, $\acute{C}$	=	Pressure loss coefficient, dimensionless
C_i	=	Nozzle coefficients, dimensionless
$\bar{C}$	=	Friction rate coefficient, $Pa\cdot s^n/(m\cdot L^n)$ [(in. water/(100 ft$\cdot$cfm^n)]
D_h	=	Hydraulic diameter, m (ft)
f_{meas}	=	Measured Darcy friction factor, dimensionless
f_{calc}	=	Calculated Darcy friction factor, dimensionless
H	=	Height, mm (in.)
$L_{1\text{-}2}$	=	Total test duct length, m (ft)
$\dot{m}$	=	Mass flow rate, kg/s (lb_m/s)
n	=	Pressure exponent, dimensionless
$\acute{n}$	=	Number of open nozzles, dimensionless
N	=	Number of data points, dimensionless
$\acute{N}$	=	Number of internal reinforcements in test section, dimensionless
p_b	=	Barometric pressure, kPa (in. Hg)
p_e	=	Saturation vapor pressure, Pa (lb_f/in^2)
p_p	=	Partial pressure, Pa (lb_f/in^2)
p_s	=	Static pressure, Pa (in. of water)
p_v	=	Velocity pressure, Pa (in. of water)
$\Delta p_{f,1\text{-}2}$	=	Duct pressure loss per unit length, Pa/m (in. of water/100 ft)
Δp_s	=	Static pressure differential between planes, Pa (in. of water)
Q	=	Volume flow rate, L/s (ft^3/min)
R	=	Ideal gas constant, kJ/($kg_{da}\cdot$K) [ft$\cdot lb_f/(lb_{m,da}\cdot$°R)]
R^2	=	Linear correlation coefficient, dimensionless
Re	=	Reynolds number, dimensionless
S_{xx}^2	=	Squared deviation of x-data, Pa^2 (in. of water^2)
S_{yx}^2	=	Square of the standard error of y-data, Pa^2 (in. of water^2)
$t_{db,o}$	=	Ambient dry-bulb temperature, °C (°F)
$t_{wb,o}$	=	Ambient wet-bulb temperature, °C (°F)
t_1	=	Test section dry-bulb temperature, °C (°F)
$t_{\alpha/2,N-1}$	=	t-statistic, dimensionless
t_5	=	Nozzle chamber approach dry-bulb temperature, °C (°F)
V	=	Average air velocity, m/s (ft/min)
W	=	Width, mm (in.)

Y	=	Nozzle expansion factor, dimensionless

GREEK SYMBOLS

β	=	Nozzle exit diameter to chamber diameter ratio, dimensionless
ε	=	Absolute roughness, mm (ft)
ε/D_h	=	Relative roughness, dimensionless
ρ	=	Density, kg/m^3 (lb_m/ft^3)
μ	=	Kinematic viscosity, Pa·s ($lb_f \cdot s/ft^2$)

SUBSCRIPTS

1	=	Test section plane at the test duct entry
2	=	Test section plane at the test duct exit
5	=	Nozzle plane upstream of the nozzle entry
6	=	Nozzle plane downstream of the nozzle exit
i	=	Index
x	=	Plane

INTRODUCTION

Phenolic ducts are a new air distribution product that is entering the North American market from Europe and China. A phenolic duct system comprises phenolic panels, fabrication methods, coupling systems, and accessories to produce pre-insulated rectangular ductwork in sections up to 13 ft (4.0 m) long, with either a 7/8 in. (22 mm) or 1-3/16 in. (30 mm) thickness for different R-values. Phenolic panels are made of a fiber-free rigid thermoset phenolic insulation core faced with embossed aluminum foil or smooth aluminum foil on both the interior and exterior of the duct. In addition, there are three transverse joint systems available to suit different installation and project specification requirements. They include (1) a four-bolt flange system, (2) drive cleats on 4-sides, and (3) butted ducts with fasteners at exterior corners and sides. Of the duct joining systems, the four-bolt flange and drive cleat systems have the same interior protrusions. The cleat system is simply two phenolic panels butted together with no internal protrusions, other than possibly not accurately aligning with each other.

SMACNA recently published the first edition of their “Phenolic Duct Construction Standards” (2015). Those standards describe structural construction requirements, but they do not include data to design phenolic duct systems. In particular, technical data such as the effects of surface roughness and flange connections on pressure drops are necessary to properly design duct systems. The objective of this research was to determine the relative and absolute roughness of phenolic duct systems connected with four-bolt flange and cleat joints, using test and data reduction procedures provided in ANSI/ASHRAE Standard 120-2017 “Method of Testing to Determine Flow Resistance of HVAC Ducts and Fittings”.

TESTED DUCT SECTIONS

Factory-fabricated ducts with seven distinct rectangular cross sections selected to provide a range of aspect ratios ($1 \leq W/H \leq 4$), as listed in Table 1, were investigated in this project. The width W and height H of the ducts were based on measured duct *internal* dimensions. The major and minor interior dimensions of the phenolic ducts, W and H, respectively, were carefully assessed across three separate planes using a tape measure, and then averaged to evaluate the test section hydraulic diameter. In every instance, the duct material thickness was 7/8 in. (22 mm), with smooth aluminum foil covering the internal surface between flanges.

Figure 1 shows the test setup and total duct lengths required by Standard 120. All of the duct lengths there are expressed in terms of hydraulic diameter D_h. For each duct cross section, two test duct section lengths were tested. The section lengths of the first test series was 10 ft (3.0 m), and for the second series, the section length was reduced by half, i.e., 5 ft (1.5 m) duct lengths. In each case, the *total* test duct length (combination of multiple duct sections) was at least 44 hydraulic diameters, with the test section comprising a minimum of 25 hydraulic diameters, per Figure 1 (excerpted from Standard 120). Table 1 also lists the number of flanges in each case, and indicates the ratio of the number of flanges in the shorter duct section case to the number in the longer duct section case. It is important to note that halving the length of the test sections essentially doubled the number of joints for the ducts tested.

The duct sections tested were assembled according to manufacturer specifications, and per the requirements in the SMACNA Phenolic Duct Construction Standards (2015). In every instance, the phenolic ducts were supplied with a four-bolt flange pre-installed on each end by the manufacturer using retaining screws to fasten the periphery of the flanges to the ends of the ducts, as depicted in Figure 2. The screws were generally spaced approximately 6 in. (150 mm) from each corner of flange, as well as at the center of the flange sides (space permitting). In every instance the screws projected as much as 1 in. (25 mm) into the flow cross section. Likewise, a stiffening ridge present on the internal surface of the flange protruded approximately 0.12 in. (3.0 mm) into the air flow cross section. Figure 3 portrays the self-adhesive foam gasket mounted on the exposed surface of each flange. This was installed in the laboratory per manufacturer requirements to minimize air leakage between the assembled duct sections. The duct sections comprising the test section were carefully aligned and secured using four bolts mounted at each corner. The bolts are apparent in Figure 4, which depicts an extra application of caulking that was applied to the four exposed corners of each flange. While not required by the manufacturer for field installations, this procedure was followed because the corners of the flanges were viewed as a possible site for air leakage. The caulking was allowed to cure for at least 24 hours before leakage and pressure loss testing began. As shown in Figure 5, cleats were utilized to pull the flange ends together to minimize any possible air leakage paths. This was accomplished using a hammer to drive the cleat over the flange connections. The final step in the installation procedure was to apply aluminum foil tape around the outside of the flange connection to the duct, in order to completely cover each of the screw heads and further reduce possible air leakage at these locations. Taping over the screw heads was likewise not required by the manufacturer. The applied tape is also displayed in Figure 5.

There were no internal or external reinforcements present in the sample ducts, with the exception of the 22 in. × 22 in. (559 mm × 559 mm) duct with a 10 ft (3.0 m) section length. Initially that particular configuration was mistakenly supplied by the manufacturer with reinforcements present; that same duct was later provided by the manufacturer without internal reinforcements. It was therein decided to test that combination of duct cross section and section length both with and without internal reinforcement, as described in greater detail in Appendix B.

TEST PROGRAM

Duct lengths upstream/downstream of the test section, as shown in Figure 1, were chosen to conform to ASHRAE Standard 120. As a cost saving measure, transformation pieces to attach the rectangular cross sections of the test ducts to the nozzle chamber were not employed in this project. Instead, more phenolic duct of the same cross-section as the test duct section was used upstream of the test section, with a minimum length of 15 hydraulic diameters. The inlet of the upstream section was attached by flanges directly to a plywood sheet mounted on the outlet of the nozzle chamber described below, as permitted by ASHRAE Standard 120.

An existing nozzle chamber in compliance with ASHRAE Standard 120 was used to measure the flow rate through the test section. The nozzle board contained four long radius spun aluminum flow nozzles. Flow settling screens located inside the chamber upstream of the nozzle board were used to make the flow more uniform before entering the flow nozzles; unused nozzles were blocked by vinyl balls. The “blow-through” mode of Standard 120 (Section 7.2 b) was employed in conjunction with a 30 hp (22 kW) blower located upstream of the nozzle chamber. Flow rates were varied by adjusting the motor speed and changing the combination of nozzles. For each pressure drop test, the blower motor was allowed to run for several minutes in order to obtain steady state conditions.